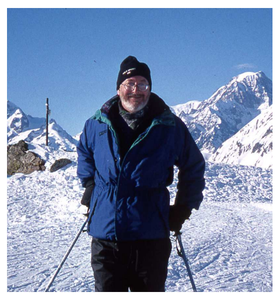
Hints of New Physics in the Decay $\Sigma^+ \to p\mu^+\mu^-$

E. Craig Dukes[a]
Physics Department, University of Virginia,
Charlottesville, VA USA



The HyperCP (E871) experiment collected $\sim 10^9$ hyperon decays in the 1997 and 1999 Fermilab fixed-target running periods. Using the data from the 1999 run, we report on the observation of three isolated events with reconstructed masses consistent with the hypothesis $\Sigma^+ \to p\mu^+\mu^-$. This is the rarest baryon decay ever observed. The dimuon mass distribution is unexpectedly narrow, suggesting the decay may proceed via an intermediate state of mass $214.3 \pm 0.5\,\mathrm{MeV}/c^2$. This state is consistent with a short-lived pseudoscalar sgoldstino with parity-conserving interactions decaying into two unlike-sign muons.

1 Introduction

The decay $\Sigma^+ \to pl^+l^-$ ($l = e, \mu$) is of interest because in the standard model it is highly suppressed, with flavor-changing-neutral-current and weak-radiative leading diagrams. Hence observation of such a decay at a level greater than expected would signal new physics. Current experimental limits on such decays are relatively weak: there is an upper bound of 7×10^{-6} on the $\Sigma^+ \to pe^+e^-$ decay mode [1], but no limit on the $\Sigma^+ \to p\mu^+\mu^-$ decay mode. Using the largest hyperon data sample ever collected, the HyperCP collaboration has searched for $\Sigma^+ \to p\mu^+\mu^-$ with hitherto unprecedented sensitivity.

---

[a]Representing the HyperCP collaboration: Y.C. Chen, *(Academia Sinica)*; W.S. Choong, G. Gidal, Y. Fu, T. Jones, K.B. Luk, P. Zyla, *(Berkeley and LBNL)*; C. James, J. Volk, *(FNAL)*; J. Felix, *(Guanajuato)*; R.A. Burnstein, A. Chakravorty, D.M. Kaplan, L.M. Lederman, W. Luebke, D. Rajaram, H.A. Rubin, C.G. White, S.L. White, *(IIT, Chicago)*; N. Leros, J.P. Perroud, *(Lausanne)*; H.R. Gustafson, M.J. Longo, F. Lopez, H.K. Park, *(Michigan)*; K. Clark, C.M. Jenkins, *(S. Alabama)*; E.C. Dukes, C. Durandet, T. Holmstrom, M. Huang, L.C. Lu, K.S. Nelson, *(Virginia)*.

2 The HyperCP Apparatus

The HyperCP experiment (Fig. 1) was designed primarily to investigate CP violation in charged Ξ and Λ hyperon decays [2]. A charged-secondary beam of 170 GeV/c average momentum was produced by steering an 800 GeV/c proton beam onto a $2{\times}2$ mm^2 cross section Cu target followed by a curved channel embedded in a 6 m long dipole magnet (hyperon magnet). Charged particles were momentum analyzed in a magnetic spectrometer employing high-rate, narrow-pitch wire chambers. The polarities of the hyperon and spectrometer magnets were periodically flipped to select oppositely charged secondary beams: the analysis reported here is from the positive-polarity data sample. At the rear of the spectrometer were two identical muon stations positioned on either side of the secondary beam. Each station had three sets of horizontal and vertical proportional-tube planes, each behind 0.81 m of iron absorber, as well as horizontal and vertical hodoscopes, which were used to trigger on muons. The analysis reported herein is from 2.14 billion unlike-sign muon triggers.

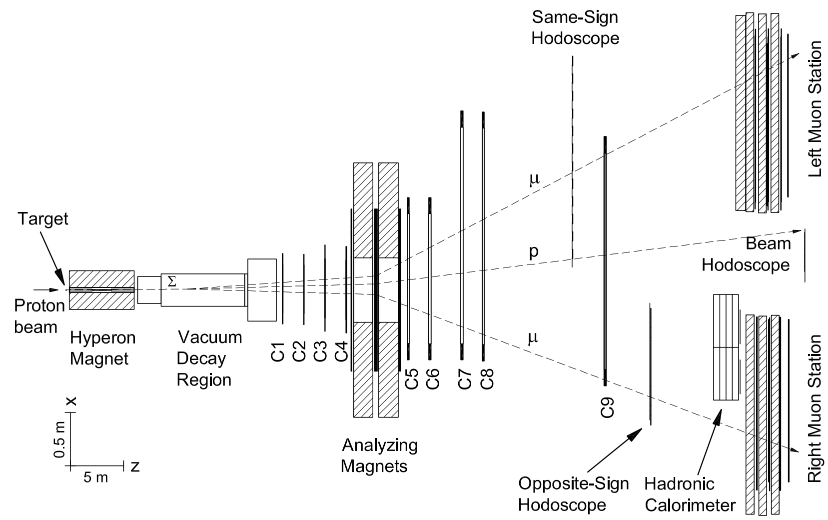


Figure 1: Plan view of the HyperCP spectrometer.

3 Selecting Events

The basic event-selection cuts required: (1) that two positively charged and one negatively charged track emanate from a common vertex with the distance-of-closest-approach less than 2.5 mm and the vertex-fit $\chi^2 < 1.5$; (2) that the decay vertex lie well within the vacuum decay region; (3) that the extrapolated track of the Σ^+ point back to within 3.5 mm of the center of the target; (4) that there be two oppositely charged tracks each with hits in two of the three muon proportional tube planes; and (5) that the highest momentum track not be a muon candidate and that it have the same sign charge as the secondary beam. To eliminate kaon decays — particularly $K^+ \to \pi^+\pi^-\pi^+$ and $K^+ \to \pi^+\mu^+\mu^-$ decays — further cuts were made on: (1) the ratio of the momentum of the non-muon track to the total momentum of the putative Σ^+:

$$f_{\text{hadron}} = \frac{\text{“hadron” momentum}}{\text{total } \Sigma^+ \text{ momentum}} \geq 0.68, \tag{1}$$

and (2) events with a $\pi^+\mu^+\mu^-$ invariant mass within 3σ of the K^+ mass. These two cuts eliminated essentially all of the kaon decays that passed the basic event-selection cuts. Figure 2 shows the $p\mu^+\mu^-$ invariant mass after application of the basic event selection cuts. Three events

are found within $1\,\sigma$ of the Σ^+ mass, and about $20\,\sigma$ from the large kaon-decay background, which with the application of the kaon-removal cuts is reduced to only four events.

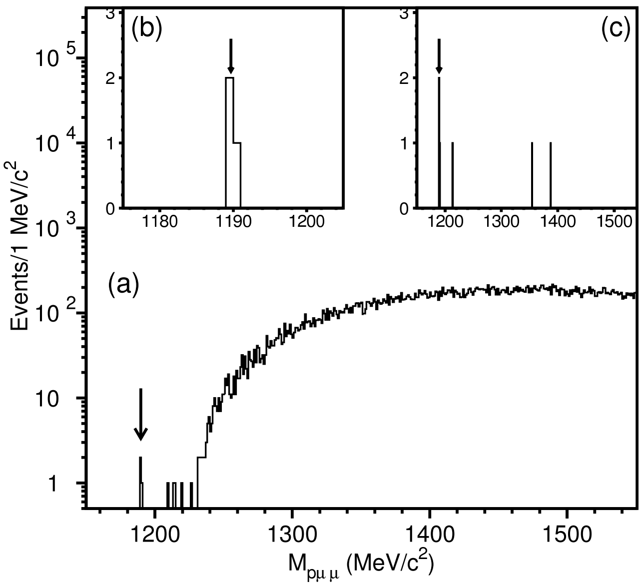


Figure 2: The $p\mu^+\mu^-$ invariant mass: (a) after basic event-selection cuts; (b) in the Σ^+ mass region; and (c) after the application of the kaon-removal cuts.

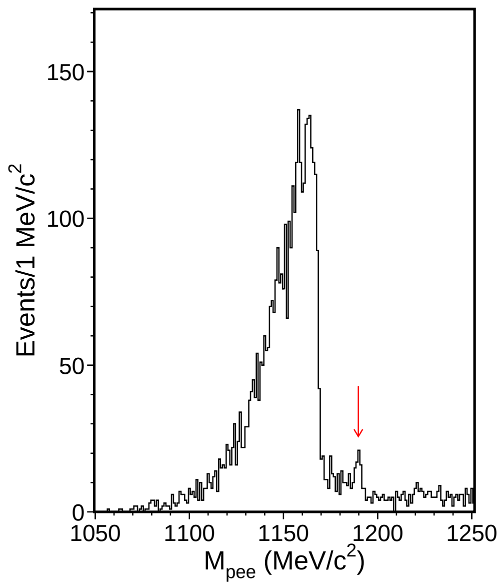


Figure 3: The pe^+e^- invariant mass from a preliminary analysis. A clear peak at the Σ^+ mass is evident. The fractions of events at the Σ^+ mass coming from true $\Sigma^+ \to pe^+e^-$ decays and from $\Sigma^+ \to p\gamma$ decays with the γ converting to e^+e^- pairs, is not known.

Much effort was spent in investigating whether the three signal events were indeed real Σ^+ decays. Backgrounds from other hyperon decays were negligible. There is no other positively charged hyperon, so hyperon background events would have to come from anti-hyperon decays, such as $\overline{\Xi}^+ \to \overline{\Lambda}\pi^+ \to \overline{p}\pi^+\pi^+$ or $\overline{\Omega}^+ \to \overline{\Lambda}K^+ \to \overline{p}\pi^+K^+$, where the pion or kaon and the antiproton are somehow misidentified as muons. In addition, the highest momentum track in such decays — almost always the antiproton — has the wrong sign charge and hence would not pass the f_{hadron} cut. Hence the likelihood of the three signal events being anti-hyperons is negligible.

More plausible hyperon-decay backgrounds are the dominant Σ^+ decay, $\Sigma^+ \to p\pi^\circ \to p\gamma\gamma$ (BR $= 0.53$), or the weak-radiative decay $\Sigma^+ \to p\gamma$ (BR $= 1.2{\times}10^{-3}$), with the gamma converting to a unlike-sign muon pair. However, the probability of a gamma converting to a $\mu^+\mu^-$ pair in the windows of the vacuum decay region, at $\sim 10^{-7}$, is negligibly small. A search for the $\Sigma^+ \to pe^+e^-$ decay mode shows evidence of a signal at the Σ^+ mass, as can be seen in Fig. 3. If gamma conversions were indeed the source of the unlike-sign muons, then since the conversion rate $\gamma \to e^+e^-$ is $\mathcal{O}(10^5)$ greater than $\gamma \to \mu^+\mu^-$, one would expect far more events in the $\Sigma^+ \to pe^+e^-$ mode: that is clearly not the case. Note that the analysis of the $\Sigma^+ \to pe^+e^-$ decay mode is much more difficult than the $\Sigma^+ \to p\mu^+\mu^-$ mode since HyperCP has no electron identification, and $\Sigma^+ \to pe^+e^-$ events from $\Sigma^+ \to p\gamma$ conversions are a non-negligible background.

We have analyzed the HyperCP negative-polarity data sample, which is about half the size of the positive-polarity sample, using the same cuts, and, as expected, we find no events at the Σ^+ mass satisfying the event-selection cuts. We also searched the single-muon trigger sample — some thirty times larger than the dimuon trigger sample (and prescaled by a factor of ten) — and, again, as expected, we find no events below 1200 MeV/c^2, indicating that backgrounds do not appear to survive the event-selection cuts. Nor did relaxing the event-selection cuts add any background events in the Σ^+ mass region.

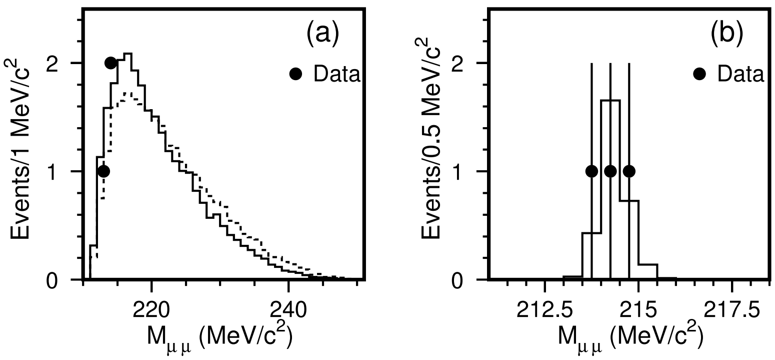


Figure 4: The $\mu^+\mu^-$ invariant mass of the three signal events with superimposed (a) Monte Carlo form factor decays (solid histogram) and uniform phase-space decays (dashed histogram), and (b) Monte Carlo $\Sigma^+ \to pX^0$, $X^0 \to \mu^+\mu^-$ events generated with $m_{X^0} = 214.3\mathrm{MeV}/c^2$.

4 Determining the Branching Ratio

Since the spectrometer acceptance was not perfect, the form factors had to be known for the branching ratio to be extracted. The four form factors describing the $\Sigma^+ \to p\mu^+\mu^-$ decay cannot be calculated ab initio, but were extracted from the branching ratio and asymmetry of the $\Sigma^+ \to p\gamma$ decay and limits on the $\Sigma^+ \to pe^+e^-$ branching ratio. The decay used as the normalization mode in determining the branching ratio was $\Sigma^+ \to p\pi^\circ$, where one of the gammas from the $\pi^\circ \to \gamma\gamma$ decay converted to an e^+e^- pair, and the other was not detected: HyperCP had no gamma detectors. We find:

$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = [8.6^{+6.6}_{-5.4}(\mathrm{stat})\pm 5.5(\mathrm{syst})]\times 10^{-8}. \tag{2}$$

Using a uniform phase-space, rather than form-factor, model for the $\Sigma^+ \to p\mu^+\mu^-$ decay increases the branching ratio by about 50%. If we assume that the three signal events are all from some unknown background then we obtain an upper limit at 90 C.L. of $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) < 3.4\times 10^{-7}$.

A theoretical calculation by Bergström et al. estimates the branching ratio to be $\sim 10^{-8}$ [3]. A more recent calculation by He at al. predicts the branching ratio to lie between 1.6×10^{-8} and 9.0×10^{-8} [4].

5 The Dimuon Mass Distribution

Unexpectedly, as shown in Fig. 4, all three signal events have dimuon masses within 1 MeV$/c^2$ of each other, which is the mass resolution of the HyperCP spectrometer. The probability that the three masses would all have the same value anywhere in the allowed kinematic range is about 1%. Varrying the form factors within their allowed ranges does not increase this probability significantly. As pointed out by He et al. [6], it is highly unlikely that this narrow mass distribution could be due to the formation of a muonium-bound state, despite the fact that the mean dimuon mass is only 3 MeV$/c^2$ higher than twice the muon mass. This suggests that the decay proceeds via an hitherto unknown intermediate state X^0 of mass 214.3±0.5 MeV$/c^2$ with a branching ratio $\mathcal{B}(\Sigma^+ \to pX^0, X^0 \to \mu^+\mu^-) = [3.1^{+2.4}_{-1.9}(\mathrm{stat})\pm 1.5(\mathrm{syst})]\times 10^{-8}$.

Unfortunately, HyperCP can say little about the putative X^0 particle's properties, outside of its mass. Searches in the kaon sector eliminate the possibility that it is a parity violating; HyperCP, for example, does not find any evidence of a dimuon mass peak in their $K^+ \to \pi^-\mu^+\mu^-$ data sample. If X^0 were a vector particle then KTeV would have seen evidence of its decay in

their $K_L \to \gamma\mu^+\mu^-$ data sample [7]. Hence, assuming its properties are not too exotic, one must assume that X^0 is a parity conserving pseudoscalar or axial vector.

It has been pointed out by Gorbunov and Rubakov that such a particle would be consistent with the sgoldstino, the superpartner to the goldstino [8]. The sgoldstino is expected to be spin 0, all of its other properties are ill determined: it can be light, long or short lived, there should be two, a scalar and a pseudoscalar, and its interactions can be flavor conserving and flavor violating, and may or may not conserve parity. The branching ratio to dimuons can be large.

6 Conclusions

This observation begs to be confirmed or refuted. Unfortunately, HyperCP has exhausted their available data, and with the Tevatron fixed-target program over at Fermilab, there are no prospects for further running. The only other similar such hyperon decay that is kinematically allowed is $\Omega^- \to \Xi^-\mu^+\mu^-$. Although HyperCP has the world's largest Ω^- sample, with an expected branching ratio of $\mathcal{O}(10^{-6})$ [6, 9], at best one would find only a few events. However, four-body kaon decay limits are comparatively weak, and modes such as $K_L \to \pi\pi X^\circ$ are expected to have branching ratios $\mathcal{O}(10^{-8})$ [6, 8, 9] and should be pursued, as well as the other possible channels discussed, for example, in Ref. [8].

We finally note that these results have recently been published in Physical Review Letters [10].

Acknowledgments

We thank the organizers for a most interesting and stimulating conference. We are indebted to the staffs of Fermilab and the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and the National Science Council of Taiwan, R.O.C. E.C.D. and K.S.N. were partially supported by the Institute for Nuclear and Particle Physics at the University of Virginia. K.B.L. was partially supported by the Miller Institute.

References

1. G. Ang *et al.*, Z. Phys. **228**, 151 (1969).
2. R.A. Burnstein *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **541**, 516 (2005).
3. L. Bergström, R. Safadi, and P. Singer, Z. Phys. C **37**, 281 (1988).
4. X.-G. He, J. Tandean, and G. Valencia, Phys. Rev. D **72**, 074003 (2005).
5. S. Eidelman *et al.*, (Particle Data Group), Phys. Lett. B **592**, 1 (2004).
6. X.-G. He, J. Tandean, and G. Valencia, Phys. Lett. B **631**, 100 (2005).
7. A. Alavi-Harati *et al.*, Phys. Rev. Lett. 87, 071801 (2001).
8. D.S. Gorbunov and V.A. Rubakov, Phys. Rev. D **73**, 035002 (2006).
9. N.G. Deshpande, G. Eilam, and J. Jiang, Phys. Lett. B **632**, 212 (2006).
10. H.K. Park *et al.*, Phys. Rev. Lett. **94**, 021801 (2005).